Liquid Phase Halogenation with Metal Halides (Commemoration Issue Dedicated to Professor Sango Kunichika On the Occasion of his Retirement)

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Liquid Phase Halogenation with Metal Halides

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Recent studies on the liquid phase halogenation of alkanes, olefins, acetylenes, and arenes with metal or metalloidal halides are reviewed. Some characteristics in these halogenation, reactions, as compared with halogenation by molecular halogens, are mentioned.

Various kinds of halogenating agents have been employed to replace a hydrogen atom in paraffinic and aromatic hydrocarbons with a halogen atom, or to add a halogen molecule to unsaturated hydrocarbons, though certain choice of reagent depending on substrate would be necessary. Liquid phase halogenation of various hydrocarbons with metal or metalloidal halides, which are mostly used in the form of higher valency states, shows interesting features in many respects, particularly in selectivities. In this paper, several recent results on these halogenation reactions, including our data are reviewed concisely, placed an emphasis on comparisons between halogen and metal halide halogenation.

I. HALOGENATION OF OLEFINS AND ACETYLENES

Several metal and metalloidal halides ($CuBr_2$, $CuCl_2$, $SbCl_5$, $TlCl_3 \cdot 4H_2O$, PCl_5, $AuCl_3$ *etc.*) have been known to effect direct halogenation of olefins or acetylenes. Various examples are collected in Table 1. Some data relating to product distribution and streochemistry are also summarized in Table 2.

Halogenation with CuX_2 (X = Br, Cl) is easily achieved in a homogeneous system using acetonitrile (with[1] or without[2] LiX) as solvent. Though other solvents such as alcohols[1,3] and acetic acid (with NaOAc)[1] can be used effectively for this reaction, the formation of solvent-incorporated products is unavoidable owing to their high nucleophilicity. The reactivity of olefins toward CuX_2 suggests that this halogenation would be surely electrophilic. As for $CuBr_2$, the reaction is completely stereospecific and *trans*; whereas in the case of less reactive $CuCl_2$, the specificity is considerably sensitive to substrate structure and reaction medium.[4] In contrast to this, the addition of bromine or chlorine to simple olefins is known to be highly stereospecific. A predominant *trans*-1,4-adduct formation from butadiene and $CuBr_2$ would be interesting, since the fact is known that the halogenation with bromine molecule affords nearly equal amounts of 1,2- and *trans*-1,4-dibromides (as kinetically controlled products) in various solvents.[5]

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Table 1. Halogenation of Olefins and Acetylenes with Metal and Metalloidal Halides

Olefin or Acetylene	Halide	Reaction Conditions	Product (Yield, %)[a]	Ref.
CH_2=CH-CH_2OH	$CuBr_2$	in CH_3OH, 64°, 24 hr	$BrCH_2CHBrCH_2OH$ (98)	3
$(CH_3)_2C$=$C(CH_3)_2$	$CuBr_2$	in CH_3CN, 25°, 5–15 min	$(CH_3)_2CBrCBr(CH_3)_2$ (91)	2
C_6H_5CH=CH_2	$CuBr_2$	in CH_3CN, 25°, 5–15 min	$C_6H_5CHBrCH_2Br$ (87)	2
CH_2=CH_2	$CuBr_2$	in CH_3CN, 25°, 5–15 min	$BrCH_2CH_2Br$ (57)	2
CH_2=CH-CN	$CuBr_2$	in CH_3CN, 60–80°, 2–4 hr	$BrCH_2CH_2BrCN$ (32)	2
C_6H_5C≡CC_6H_5	$CuBr_2$	in CH_3OH, 64°, 25 hr	*t*-C_6H_5CBr=$CBrC_6H_5$ (19)	3
C_6H_5C≡CH	$CuBr_2$	in CH_3OH, 64°, 15 hr	C_6H_5CBr=CBr_2 (67)[b]	3
CH≡C-CH_2OH	$CuBr_2$	in CH_3OH, 64°, 0.5 hr	Br_2C=$CBrCH_2OH$ (93)[b]	3
$(CH_3)_2C$=$C(CH_3)_2$	$CuCl_2$	in CH_3CN, 60–80°, 2–4 hr	$(CH_3)_2CClCCl(CH_3)_2$ (53)	2
CH_2=CH_2	$CuCl_2$	in CH_3CN, 60–80°, 2–4 hr	$ClCH_2CH_2Cl$ (32)	2
C_6H_5CH=CH_2	$CuCl_2$	in AcOH+NaOAc, 90°, 5 hr	$C_6H_5CHClCH_2Cl$ (71)	1
C_6H_5CH=CH_2	$CuCl_2$	in CH_3CN+LiCl, 82°, 10 hr	$C_6H_5CHClCH_2Cl$ (74)	1
CH_2=CH-CN	$CuCl_2$	in CH_3CN+LiCl, 82°, 22 hr	$ClCH_2CHClCN$ (42)	16
CH≡C-CH_2OH	$CuCl_2$	in CH_3OH, 64°, 22 hr	Cl_2C=$CClCH_2OH$ (23)[b]	3
n-$C_6H_{13}CH$=CH_2	$SbCl_5$	in CCl_4, 30–35°, 10 min	*n*-$C_6H_{13}CHClCH_2Cl$ (~100)	8
n-$C_6H_{13}CH$=CH_2	$TlCl_3 \cdot 4H_2O$	in CCl_4, 77°, 2 hr	*n*-$C_6H_{13}CHClCH_2Cl$ (26)	11
n-$C_6H_{13}CH$=CH_2	PCl_5	in C_6H_5Cl, 91°, 6 hr	*n*-$C_6H_{13}CHClCH_2Cl$ (83)	12

a. Mostly based on metal halides charged.

b. The product may be formed through three following steps.

$$HC{\equiv}CR \longrightarrow XCH{=}CRX \longrightarrow X_2CH{-}CRX_2 \longrightarrow X_2C{=}CRX$$

Informations on the reaction mechanism of this type of halogenation have been obtained from recent kinetic studies. For the reaction with $CuCl_2$, a mechanism involving an electrophilic attack of $CuCl_2$ molecule (eq. 1) has been suggested, based on rather

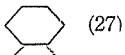
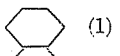
$$>C{=}C<+CuCl_2 \longrightarrow >C(CuCl_2){=}C< \xrightarrow{(a)} >C(\delta^+Cl\text{–}CuCl^{\delta-})\text{–}C< \xrightarrow[(b)]{CuCl_2} >CCl\text{–}CCl< \qquad (1)$$

(rate-detg. step: (a) in acetonitrile, (b) in *n*-propanol)

complex rate equations obtained in the chlorination of styrene in both acetonitrile-LiCl and *n*-propanol.[1] More recently, it is shown that, in the chlorination of 1-octene in methanol, the observed rate expression almost agrees with the above mechanism, though in which the rate-determining attack of Cl^- rather than $CuCl_2$ (at step (b)) is more probable.[6] In addition, in view of the lack of stereospecificity, an unsymmetrically-bridged cationic intermediate is proposed instead of a symmetrically-bridged one.[6] In the case of $CuBr_2$, the bromination rate of *n*-hexene in methanol has been found to obey simple third-order kinetics (nearly second-order to $CuBr_2$ and first-order to the olefin), and a suggested mechanism is essentially identical to that shown in eq. 1.[7] Here no positive evidence for the generation of free bromine from $CuBr_2$ (eq. 2) is found. In

$$2CuBr_2 \rightleftarrows 2CuBr+Br_2 \qquad (2)$$

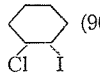
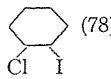
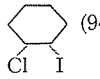
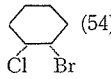
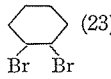
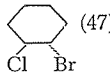
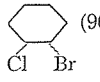
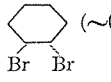
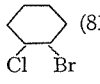
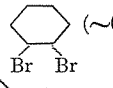
Table 2. Product Distribution and Stereochemistry in Halogenation of Olefins

Substrate	Halogen source	Reaction Conditions	Product (Yield, %)	trans Addition	Ref.
c-CH_3-CH=CH-CH_3	Br_2	in CH_3CN, 25°	*dl*-$CH_3CHBrCHBrCH_3$	100	16
c-CH_3-CH=CH-CH_3	$CuBr_2$	in CH_3CN, 25°, 10 min	*dl*-$CH_3CHBrCHBrCH_3$ (91)	100	2
t-CH_3-CH=CH-CH_3	Cl_2	in $CF_2ClCFCl_2$, −9°	*meso*-$CH_3CHClCHClCH_3$	100	17
t-CH_3-CH=CH-CH_3	$CuCl_2$	in CH_3OH, 140°, 3 hr	*meso*- & *dl*-$CH_3CHClCHClCH_3$ (10)	62	4
t-CH_3-CH=CH-CH_3	$SbCl_5$	in CCl_4, 76°, 10 min	*meso*- & *dl*-$CH_3CHClCHClCH_3$ (96)	18	8
	Br_2	in CH_3CN, 0°, 1.5 hr	 (63) &  (27)	100	2
	$CuBr_2$	in CH_3CN, 0°, 1.5 hr	 (93) &  (1)	100	2
	Cl_2	in CCl_4, 0°, 10 min		100	9
	$CuCl_2$	in CH_3CN, 60–80°, 2–4 hr	*c*- & *t*-  (73)	95	2
	$CuCl_2$	in AcOH, 150°, 2 hr	*c*- & *t*- 	88	4
	$SbCl_5$	in CCl_4, 76°, 5 min	*c*- & *t*-  (67)	17	8
	$TlCl_3 \cdot 4H_2O$	in CCl_4, 76°, 2 hr	*c*- & *t*-  (17)	98	11
	PCl_5	neat, 80°, 10 hr	 (87)	100	12
CH_2=CH-CH=CH_2	$CuBr_2$	in CH_3CN, 25°, 10 min	only *t*-$BrCH_2CH$=$CHCH_2Br$ (92)	—	2
CH_2=CH-CH=CH_2	$CuCl_2$	in CH_3CN, 60°, 2–4 hr	a mixture of $CH_2ClCHCl$-CH=CH_2, *c*- & *t*-$ClCH_2CH$=$CHCH_2Cl$ (43) (ratio 15 : 5 : 80)	—	2
CH_2=CH-CH=CH_2	$SbCl_5$	in CCl_4, 0°, 10 min	a mixture of $CH_2ClCHCl$-CH=CH_2, *c*- & *t*-$ClCH_2CH$=$CHCH_2Cl$ (50) (ratio 32 : 21 : 47)	—	9
	Cl_2	in CH_3CN, 6–11°	*c*- & *t*-  (trace amounts)	95	18
	$CuCl_2$	in CH_3CN+ LiCl, 82°, 22 hr	*c*- & *t*-  (58)	70	18

$CuBr_2$-acetonitrile system, however, a somewhat different situation has been known, *i.e.*, a spectrophotometric evidence is present for the dissociation of $CuBr_2$ according to eq. 3, and the bromination of olefins in acetonitrile is extremely rapid compared to the reaction

$$2CuBr_2 \rightleftarrows \frac{1}{2}Br_2 + Cu^+ + CuBr_3^- \quad (3)$$
$$\uparrow \quad\quad\quad\

Table 3. Mixed Halogenation of Olefins with Mixtures of Metal Halides and Halogen Donors

Olefin	Metal Halide & Halogen Donor (molar ratio)	Reaction Conditions	Product (Yield %)	Ref.
$CH_2=CH_2$	$CuCl_2+I_2$ (2:1)	in C_6H_{12}, 80°, 2 hr	ICH_2CH_2Cl (85)	2
$CH_2=CH-OCOCH_3$	$CuCl_2+I_2$ (2:1)	in CH_3CN, 25°, 2 hr	$CH_2ICHCl(OCOCH_3)$ (83)	2
$CH_3CH=CH_2$	$CuCl_2+I_2$ (2:1)	in CH_3CN, 50°, 2 hr	$CH_3CHClCH_2I$ (64) & CH_3CHICH_2Cl (21)	2
$CH_2=CH-Cl$	$CuCl_2+I_2$ (2:1)	in CH_3CN, 50°, 15 hr	CH_2ICHCl_2 (57) & $CH_2ClCHClI$ (24)	2
$(CH_3)_2C=CH_2$	$HgCl_2+I_2$ (1:2)	in $(C_2H_5)_2O$, 25°, 1 hr	$(CH_3)_2CClCH_2I$ (67)	13
$C_6H_5CH=CH_2$	$CuCl_2+KI$ (2:1)	in CH_3CN, 80°, 1 hr	$C_6H_5CHClCH_2I$ (75)	2
	$CuCl_2+I_2$ (2:1)	in CH_3CN, 80°, 2 hr	 (90)	2
	$CuCl_2+KI$ (2:1)	in CH_3CN, 80°, 2 hr	 (78)	2
	$SbCl_5+I_2$ (1:1)	in CCl_4, 76°, 10 min	 (94)	14
	$CuCl_2+Br_2$ (2:1)	in CH_3CN, 80°, 1 hr	 (54) &  (23)	2
	$CuCl_2+NH_4Br$ (2:1)	in CH_3CN, 80°, 1 hr	 (47) &  (3)	2
	$SbCl_5+Br_2$ (1:1)	in CCl_4, 30°, 5 min	 (96) &  (~0)	14
	$SbCl_5+LiBr$ (1:1)	in CCl_4, 76°, 5 min	 (81),  (~0) & *c*-, *t*-  (trace)	14
$C_6H_5CH=CH_2$	$SbCl_3+Br_2$ (1:1)	in CCl_4, 0°, 10 min	$C_6H_5CHClCH_2Br$ (87)	14

trans fashion with high stereospecificity, and the products are generally in accord with Markovnikov's rule. No competitive iodination is found in chloroiodination; whereas considerable competition with bromine is observed in chlorobromination, depending on the redox combination. This is largely due to differences in reactivities between halogens and mixed halogens (relative reactivities[15]; $I_2 : ICl = 1 : 10^5$, $Br_2 : BrCl = 1 : 4\times10^2$). In addition, if the formation of a mixed halogen proceeds through an ionic adduct (*e.g.*, eq. 7), the Lewis acidity of an original metal halide would become an important factor

$$SbCl_5+Br_2 \rightleftarrows [SbCl_5Br]^-Br^+ \rightleftarrows SbCl_4Br+BrCl \qquad (7)$$

for the concentration of a mixed halogen. In fact, it has been found[14] that the product selectivity in chlorobromination decreases as the Lewis acidity of metal chlorides decreases.

II. HALOGENATION OF ARENES

For the halogenation of rather reactive aromatics, the use of various metal or metalloidal halides ($SbCl_5$, $FeCl_3$, VCl_4, $MoCl_5$, PCl_5, $TlCl_3 \cdot 4H_2O$, $CuBr_2$, $TlBr_3 \cdot 4H_2O$ *etc.*) as halogenating agents has been reported. Representative examples are summarized in Table 4. Isomer distribution and relative rate data in the halogenation of toluene using various halogenating agents are collected in Table 5.

Based on the reactivity toward aromatics and the favorable *ortho-para* orientation, the halogenation with Lewis acid halides is considered to proceed by an electrophilic

Table 4. Aromatic Halogenation with Metal Halides

Aromatic compound	Halogenating agent	Reaction Conditions	Product (Yield, %; *o*/*p* ratio)	Ref.
C_6H_5Cl	$SbCl_5$	neat, 41–59°, 2 hr	$C_6H_4Cl_2$ (82 ; 0.2)	20
C_6H_5Cl	$FeCl_3$	neat, 125–140°, 3 hr	$C_6H_4Cl_2$ (86 ; 0.1)	19
C_6H_5Cl	VCl_4	neat, 118–121°, 2.5 hr	$C_6H_4Cl_2$ (70 ; 0.2)	21
C_6H_5Cl	$MoCl_5$	neat, 105–110°, 2.5 hr	$C_6H_4Cl_2$ (31 ; 0.1)	21
$C_6H_5CH_3$	$SbCl_5$	neat, 18–31°, 2.5 hr	$CH_3C_6H_4Cl$ (87 ; 0.9)	20
$C_6H_5CH_3$	$TlBr_3 \cdot 4H_2O$	in CCl_4, 78°, 1 hr	$CH_3C_6H_4Br$ (20 ; 1.6)	24
$C_6H_5CH_3$	$TlCl_3 \cdot 4H_2O$	in CCl_4, 78°, 2 hr	$CH_3C_6H_4Cl$ (28 ; 1.0) & $CH_3C_6H_4COOH$(10;0.7)	22
Anthracene	$CuCl_2$	in CCl_4, 78°, 7 hr	9-Chloroanthracene (98)	27
C_6H_5OH	$CuCl_2$	in DMF+LiCl, 150°, 5 min	ClC_6H_4OH (60 ; 0.1–0.2)	25
β-$C_{10}H_7OH$	$CuBr_2$	in aq. CH_3OH+KBr, 25°, 15 hr	α-Bromo-β-naphthol (50)	26
C_6H_6	AlI_3+CuCl_2	neat, 80°, 5 hr	C_6H_5I (65)	28
$C_6H_5CH_3$	$FeI_2 \cdot 4H_2O$ $+CuCl_2$	neat, 110°, 3 hr	$CH_3C_6H_4I$ (81 ; 1.1)	28
C_6H_5OH	I_2+CuCl_2	in C_6H_5Cl, 130°, 29 hr	*p*-IC_6H_4OH (69)	28
$C_6H_5N(CH_3)_2$	I_2+CuCl_2	in C_6H_6, 60°, 0.5 hr	*p*-$IC_6H_4N(CH_3)_2$ (47)	28

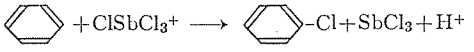
Table 5. Isomer Distibution and Relative Rate in Halogenation of Toluene

Halogen source	Reaction Conditions	Halotoluene				Ref.
		Isomer Ratio			Rel. Rate k_T/k_B	
		o	*m*	*p*		
Cl_2	in aq. CH_3COOH, 25°	60	0.5	39.5	345	29
Cl_2($SbCl_5$ cat)	neat, 25–30°	72	2	26	—	20
$SbCl_5$	neat, 18–31°	47	2	51	—	20
Cl_2($TlCl_3 \cdot 4H_2O$ cat)	in CCl_4, 78°	64	0	36	43	23
$TlCl_3 \cdot 4H_2O$	in CCl_4, 78°	52	0	48	26	23
$FeCl_3$	neat, 50–60°	12	<1	88	—	19
VCl_4	neat, 7–25°	15	1	84	—	21
Br_2	in aq. CH_3COOH, 25°	33	0	67	605	29
Br_2($TlBr_3 \cdot 4H_2O$ cat)	in CCl_4, 78°	58	0	42	7	24
$TlBr_3 \cdot 4H_2O$	in CCl_4, 78°	62	0	38	15	24

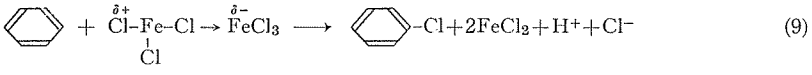
substitution. The rough chlorinating ability is given in the following order; $SbCl_5$> $FeCl_3$, VCl_4>$MoCl_5$, $CuCl_2$, and this correlates well with their oxidizing ability.[19~21] Though the activity of $TlCl_3 \cdot 4H_2O$ appears to be rather low, the reaction with this chloride in carbon tetrachloride shows somewhat different behavior, *i.e.*, conversion of benzene into chlorobenzene and benzoic acid occurs concurrently.[22]

Isomer distributions in metal chloride chlorination of toluene are clearly different from those in chlorination using chlorine molecule without or with metal chloride catalysts. This implies that metal chloride can effect substitution without prior degradation to free chlorine and the electrophiles here would be species other than Cl_2 and Cl^+. When $SbCl_5$ or $TlCl_3 \cdot 4H_2O$ is the reagent, somewhat lower *o*/*p* ratios and considerably low k_T/k_B value are obtained, and this suggests that a reactive and somewhat bulky attacking species, such as $SbCl_4^+$ and $TlCl_2^+$, may function (see eq. 8).[20,23] In cases of $FeCl_3$, VCl_4,

$$2SbCl_5 \rightleftarrows [Cl_4\overset{\delta+}{S}bCl \rightarrow \overset{\delta-}{S}bCl_5] \rightleftarrows SbCl_4^+ + SbCl_6^- \qquad (8)$$



and $MoCl_5$, the attack of a polarized dimer complex, which is more bulky, has been postulated on the basis of quite less *ortho*-substitution (see eq. 9).[19,21]



$$\qquad (9)$$

On the other hand, the selectivity data in the bromination with $TlBr_3 \cdot 4H_2O$ indicate that the reaction is essentially the same as that with bromine in the presence of $TlBr_3$ catalyst.[24]

Though CuX_2 can also act as aromatic halogenating agents, this halogenation seems to be applicable to highly reactive aromatic components, such as phenols,[25,26] aromatic amines,[26] and polynuclear hydrocarbons.[27] An interesting use of this halogenation would be the preparation of *p*-halogenated compounds of phenols and anilines. In this reaction *para*-substitution predominates, whereas usual halogenation affords a mixture of *o*- and *p*-halogenated, and/or polyhalogenated compounds.

Aromatic iodination with $CuCl_2$-iodine donor combinations (*cf.* eq. 5 and 6) has recently been developed.[28] Some examples are included in Table 4. FeI_2 and AlI_3 exhibit higher reactivity than iodine itself. The reaction would be essentially electrophilic, and is not applicable to strongly deactivated aromatics (*e.g.*, benzoic ester). Aromatics possessing functional groups that coordinate with copper salt (*e.g.*, aniline, thiophene) are often not iodinated.

III. HALOGENATION OF ALKANES

The halogenation of aliphatic hydrocarbons with chlorine or bromine molecule is usually performed in the presence of light. A few metal or metalloidal halides (*e.g.*, PCl_5, $SbCl_5$, $FeCl_3$ *etc.*) can be used in place of halogen elements. Some examples are given in Table 6.

PCl_5 can react smoothly with alkanes in an inert solvents such as *o*-dichlorobenzene

Table 6. Halogenation of Some Aliphatic Compounds with Metal and Metalloidal Halides

Substrate	Halide	Reaction Conditions	Product (Yield, %)	Ref.
n-C_7H_{16}	PCl_5	in o-$C_6H_4Cl_2$, BPO cat, 90°, 8 hr	Mixed chloroheptanes (73)	12
	PCl_5	in o-$C_6H_4Cl_2$, BPO cat, 88°, 7 hr	 -Cl (70)	12
Adamantane	$SbCl_5$	in CH_2Cl_2, 40°, 3 hr	1- & 2-Chloroadamantane (69)	31
$C_6H_5CH_2CH_3$	PCl_5	neat, 105°, 16 hr	$C_6H_5CHClCH_3$ (60)	12
$(C_6H_5)_3CH$	PCl_5	neat, 140–150°, 18 hr	$(C_6H_5)_3CCl$ (93)	35
$CH_3CH_2CH_2CHO$	$CuBr_2$	in CH_3OH, 64°, 9 hr	$CH_3CH_2CHBrCH(OCH_3)_2$ (40)	3
$CH_3CH_2CH_2CHO$	$CuCl_2$	in DMF, 85°, 2 hr	$CH_3CH_2CHClCHO$ (60)	3
$CH_3COC_2H_5$	$CuCl_2$	in DMF+LiCl, 80–90°, 0.75 hr	$CH_3COCHClCH_3$ (*ca.* 60)	25
$C_6H_5COC_2H_5$	$CuCl_2$	in DMF+LiCl, 80–90°, 1 hr	$C_6H_5COCHClCH_3$ (72)	25

to yield alkyl chlorides, in the absence or presence of an initiator (*e.g.*, benzoyl peroxide).[12] Owing to a radical nature of the reaction, the product generally consists of a mixture of isomeric chlorides except for some cases such as the chlorination of unsubstituted cycloalkanes and monoalkylated aromatics. Interestingly, the reaction with olefins affords only dichlorides (*cf.* section I), and does not cause any attack on allyl position in olefins even in the presence of peroxide. Through competitive experiments between toluene and cyclohexane, it has been found that the thermal PCl_5 reaction has almost the same selectivity as photochlorination (relative reactivities: toluene/cyclohexane (both per C-H), PCl_5 reaction 3.0, photoreaction 2.8). Thus the attacking entity is probably a chlorine atom formed through eq. 10[12] On the other hand, in the peroxide-catalyzed

$$PCl_5 \rightleftarrows PCl_3+Cl_2, \qquad Cl_2 \rightleftarrows 2Cl\cdot \tag{10}$$

Table 7. Isomer Distribution in Chlorination of n-Heptane and Adamantane

(a) Chlorination of n-Heptane (Ref. 30)

Halogene source	Reaction Conditions	x-Chloro-n-heptane			
		1-	2-	3-	4-
Cl_2	BPO cat., 98°	15.1	34.6	33.8	16.5
PCl_5	BPO cat., 98°	2.5	36.4	41.5	19.5
PCl_3+Cl_2	BPO cat., 98°	traces	24.0	52.0	24.0

(b) Chlorination of Adamantane (Ref. 31)

Halogene source	Reaction Conditions	Chloroadamantane 1/2 ratio
Cl_2	in $SnCl_4$ (ϵ=2.87), 100°, 5 min	0.6
Cl_2	in CH_2Cl_2 (ϵ=9.08), 40°, 3 hr	0.5
$FeCl_3$	in $SnCl_4$, 110°, 3 hr	9–10
$FeCl_3$	in CH_2Cl_2, 40°, 7 hr	20
$SbCl_5$	in $SnCl_4$, 110°, 15 min	9–10
$SbCl_5$	in CCl_2FCClF_2 (ϵ=2.24), $AlCl_3$ added, 40°, 20–30 min	>90

chlorination of *n*-heptane with PCl_5 and with Cl_2, somewhat different isomer distributions have been observed (see Table 7).[30] A suggested scheme[12] involving the attack of $\cdot PCl_4$ (partly $\cdot Cl$) (eq. 11) would be reasonable.

$$\left.\begin{aligned} &R\cdot + PCl_5 \longrightarrow RCl + \cdot PCl_4 \\ &RH + \cdot PCl_4 \longrightarrow R\cdot + HCl + PCl_3 \\ &\cdot PCl_4 \rightleftarrows PCl_3 + Cl\cdot \\ &RH + \cdot Cl \longrightarrow R\cdot + HCl \end{aligned}\right\} \quad (11)$$

A similar reaction of $FeCl_3$ or $SbCl_5$ with C-H linkages has also been known.[31] A radical nature of the reaction has been revealed by comparison of isomer distributions in chlorination of adamantane using various reagents such as Cl_2, $FeCl_3$, $SbCl_5$, and $SbCl_5+AlCl_3$ (see Table 7). $SbCl_5$ reacts generally at a more rapid rate than $FeCl_3$. Further, photolytic conditions enhance the rate of the $SbCl_5$ process, but does not promote the reaction with $FeCl_3$. This implies that $SbCl_5$ may be involved in a radical chain process, whereas the $FeCl_3$ reaction is probably a nonchain process. Based on these results the following radical pathway has been proposed for each chlorination.[31]

$$\left.\begin{aligned} &AdH + FeCl_3 \longrightarrow Ad\cdot + FeCl_2 + HCl \\ &Ad\cdot + FeCl_3 \longrightarrow AdCl + FeCl_2 \end{aligned}\right\} \quad (12)$$

$$\left.\begin{aligned} &AdH + SbCl_5 \longrightarrow Ad\cdot + HCl + \cdot SbCl_4 \\ &Ad\cdot + SbCl_5 \longrightarrow AdCl + \cdot SbCl_4 \\ &AdH + \cdot SbCl_4 \longrightarrow Ad\cdot + HCl + SbCl_3 \end{aligned}\right\} \quad (13)$$

Since a slight favorable effect on the rate is observed in a more polar solvent, the contribution of somewhat polar forms in the transition state may be considered. A similar situation has been known for hydrogen abstraction reactions involving chlorine atom.

$$[Ad : H \cdots Cl : FeCl_2] \longleftrightarrow [Ad\cdot \quad H : Cl \quad FeCl_2] \longleftrightarrow [Ad^+ \quad H\cdot \quad Cl^- \quad FeCl_2]$$

In the halogenation of enolizable aldehydes or ketones, the use of CuX_2 instead of halogen elements has been reported.[25] The reaction proceeds smoothly in dimethylformamide solution. Some examples are included in Table 6. This reaction is essentially the same as the halogenation of phenols with CuX_2 (*cf.* section II). As a probable pathway, the following scheme involving two-electron reduction of Cu(II) within a metal chloride–enolate complex has been suggested.[25] The observed rates of the chlorination of

$$R\text{-}\overset{OH}{\overset{|}{C}}\text{=}CHR' \xrightarrow{CuCl_2} R\text{-}\overset{O\text{-}CuCl}{\overset{|}{C}}\text{=}CHR' \longrightarrow R\text{-}\overset{O}{\overset{\|}{C}}\text{-}\overset{Cl}{\overset{|}{C}}HR' + Cu^\circ \quad (14)$$

acetone in water[32] and methanol,[33] which are approximately expressed as a sum of second- and third-order terms, seem to agree with this mechanism. Here, the contribution of the third-order term appears to imply that an external attack of Cl^-(or $CuCl_2$) on the complex may occur concurrently. A similar halogenation with $FeCl_3$ in acetic acid has also been reported.[34]

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